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NONINVASIVE CARBON DIOXIDE MONITORING IN A PORCINE MODEL OF ACUTE LUNG INJURY DUE TO SMOKE INHALATION AND BURNS

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ABSTRACT In critically ill intubated patients, assessment of adequacy of ventilation relies on measuring partial pressure of arterial carbon dioxide ($Paco_2$), which requires invasive arterial blood gas analysis. Alternative noninvasive technologies include transcutaneous CO_2 ($tPco_2$) and end-tidal CO_2 ($Etco_2$) monitoring. We evaluated accuracy of $tPco_2$ and $Etco_2$ monitoring in a porcine model of acute lung injury (ALI) due to smoke inhalation and burns. Eight anesthetized Yorkshire pigs underwent mechanical ventilation, wood-bark smoke inhalation injury, and 40% total body surface area thermal injury. $tPco_2$ was measured with a SenTec system (SenTec AG, Therwil, Switzerland) and $Etco_2$ with a Capnostream-20 (Oridion Medical, Jerusalem, Israel). These values were compared with $Paco_2$ measurements from an arterial blood gas analyzer. Paired measurements of $Etco_2$-$Paco_2$ (n 276) and $tPco_2$-$Paco_2$ (n 250) were recorded in the $Paco_2$ range of 25 to 85 mmHg. Overlapping data sets were analyzed based on respiratory and hemodynamic status of animals. Acute lung injury was defined as $Pao_2/Fio_2 \leq 300$ mmHg; hemodynamic instability was defined as mean arterial pressure ≤ 60 mmHg. Before ALI, $Etco_2$ demonstrated moderate correlation with $Paco_2$ (R^2 0.45; $P < 0.0001$), which deteriorated after onset of ALI (R^2 0.12; $P < 0.0001$). Before ALI, $tPco_2$ demonstrated moderate correlation (R^2 0.51, $P < 0.0001$), which was sustained after onset of ALI (R^2 0.78; $P < 0.0001$). During hemodynamic stability, $Etco_2$ demonstrated moderate correlation with $Paco_2$ (R^2 0.44; $P < 0.0001$). During hemodynamic instability, $Etco_2$ did not correlate with $Paco_2$ (R^2 0.03; P 0.29). $tPco_2$ monitoring demonstrated strong correlation with $Paco_2$ during hemodynamic stability (R^2 0.80, $P < 0.0001$), which deteriorated under hemodynamically unstable conditions (R^2 0.39; $P < 0.0001$). Noninvasive carbon dioxide monitors are acceptable for monitoring trends in $Paco_2$ under conditions of hemodynamic and pulmonary stability. Under unstable conditions, reevaluation of patient status and increased caution in the interpretation of results are required.

KEYWORDS Transcutaneous carbon dioxide, end-tidal carbon dioxide, blood gas analysis, acute lung injury, swine, burns, inhalation injury

INTRODUCTION

Measurement of the partial pressure of carbon dioxide in arterial blood ($Paco_2$) remains the criterion standard for evaluating the adequacy of ventilation. In certain populations, such as trauma patients with head injury, providing appropriate ventilation (avoiding either overventilation or underventilation) has been shown to save lives (1–2). Obtaining blood gas samples, however, is invasive and requires special equipment, which is often impractical in prehospital settings. Thus, a noninvasive means of estimating $Paco_2$ would be useful (3). Several such methods have been developed.

End-tidal carbon dioxide ($Etco_2$) monitoring is performed with increasing frequency in injured patients (4,5). However, this method may become inaccurate in unstable trauma patients (6). The $Paco_2$-$Etco_2$ gradient is related to the physiologic dead space as described by Enghoff modification of the Bohr equation (7). $Paco_2$-$Etco_2$ gradient increases with increasing physiologic dead space, due to lung injuries or decreased pulmonary perfusion.

Another noninvasive technique that can be used as a surrogate for $Paco_2$ is the measurement of the transcutaneous partial pressure of CO_2 ($tPco_2$). This technique was pioneered by Severinghaus (8) in the 1960s using a temperature-stabilized heated electrode. Transcutaneous gas tension is a function of dermal capillary blood and in turn of arterial blood flow. Previous studies by Nishiyama et al. (9, 10) demonstrated good correlations between transcutaneous CO_2 measurements and $Paco_2$ in adults undergoing general anesthesia. Several studies, performed in critically ill adults (11–14) as well as in adults undergoing noninvasive ventilation (15, 16), reported good correlation between $tPco_2$ measurements and $Paco_2$. Most notably, a study by Hinkelbein et al. (13) demonstrated the feasibility of $tPco_2$ monitoring in critically ill adults during interhospital transport.

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All work has been performed at the US Army Institute of Surgical Research, Ft Sam Houston, Texas.

This study has been conducted in compliance with the Animal Welfare Act, the Implementing Animal Welfare Regulations and in accordance with the principles of the Guide for the Care and Use of Laboratory Animals.

This study has been approved by the US Army Institute of Surgical Research Institutional Animal Care and Use Committee.

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TABLE 1. **Animal data**

Weight, kg	45.0 ± 2.8
Total smoke volume, L	27.6 ± 4.9
Post smoke-inhalation arterial COHb, %	88.3 ± 4.1
Time to ALI, h	22.5 ± 10.6
Survival time, h	56.8 ± 40.9

COHb indicates carboxyhemoglobin.

Nevertheless, there is a paucity of studies comparing Et_{CO_2} and tP_{CO_2} monitoring in settings of evolving acute lung injury (ALI). Therefore, we carried out an animal study to evaluate the usability and accuracy of these methods in a clinically relevant porcine model of ALI secondary to smoke inhalation and burns.

MATERIALS AND METHODS

This study was approved by the US Army Institute of Surgical Research Animal Care and Use Committee. It was conducted in compliance with the Animal Welfare Act and the implementing Animal Welfare Regulations and in accordance with the principles of the *Guide for the Care and Use of Laboratory Animals*.

Animal preparation

For this study, we selected a subgroup of eight female, nonpregnant, Yorkshire pigs from an ongoing study that investigates treatment of acute respiratory distress syndrome (ARDS) due to smoke inhalation and burns. Total intravenous anesthesia with ketamine HCL (20 30 mg/kg per hour), midazolam HCL (1.0 1.5 mg/kg per hour), and propofol (100 μg/kg per hour) was used during the experiment. All animals underwent tracheostomy and placement of central and arterial lines. After instrumentation, animals were allowed to recover for 2 to 3 h. After stabilization, they received inhalation injury with 22 breaths of pine bark smoke at room temperature (Table 1). This model of smoke inhalation injury has been described previously (17). Smoke injury was followed immediately by a 40% total body surface area, full thickness flame burn. Upon completion of smoke inhalation and burn, animals were transferred to the animal intensive care unit where they were continuously monitored for the duration of the experiment. Total intravenous anesthesia levels were adjusted to effect as needed to attain no response to painful stimuli. In addition, buprenorphine HCl (0.1 mg/kg) was administered intramuscularly every 6 h for analgesia for the duration of the study. Resuscitation with lactated Ringer's solution was performed by means of a computerized burn resuscitation decision support system for the first 24 h after burn. Subsequently, the fluid rate was adjusted manually to achieve a urinary output of at least 0.5 mL/kg per hour. Controlled mechanical ventilation (CMV) was initiated, with a tidal volume of 10 mL/kg and a respiratory rate adjusted to maintain $Paco_2$ between 35 and 45 mmHg. Before onset of ARDS, positive end expiratory pressure was set to 5 cm H_2O and remained constant. Fraction of inspired oxygen (Fio_2) was titrated to achieve peripheral oxygen saturation (Spo_2) at or above 90%. Fiberoptic bronchoscopy for pulmonary toilet was performed at 1, 2, 6, 12, and 24 h after injury, every 24 h thereafter, and anytime airway obstruction was clinically suspected. During suctioning and bronchoscopies, Fio_2 was increased to 100%. After the onset of ARDS, animals were transitioned to low tidal volume CMV, and further ventilator changes, including adjustments of positive end expiratory pressure and Fio_2, were made in accordance with the ARDSnet protocol (18). The study was designed to continue for up to 7 days after injury. Experiments were terminated earlier if ARDS did not develop in 72 h after injury or if an animal reached terminal cardiopulmonary failure before 7 days. Animals were killed with intravenous injection of 20 mL Fatal Plus (Vortech Pharmaceuticals, Dearborn, Mich).

Ratio of the partial pressure of oxygen in arterial blood (Pao_2) to the fraction of inspired oxygen (PFR) was measured at baseline, 2 h after injury, and every 6 h thereafter. A single set of baseline measurements was recorded after surgery but before the induction of smoke inhalation and burns. Baseline duration generally was 2 to 3 h and was adequate to provide stabilization time for all vital signs after surgical preparation. We defined ALI as a sustained PFR less than 300 mmHg, and ARDS as a sustained PFR less than 200 mmHg. As an index of pulmonary instability, we recorded the frequency of changes in the respiratory rate (as set on the ventilator) and in the Fio_2. We defined hemodynamic instability as mean arterial pressure (MAP) of 60 mmHg or less (or a requirement for norepinephrine infusion to maintain MAP >60 mmHg).

A SenTec Digital Monitor and V Sign digital sensor (SenTec Ag, Therwil, Switzerland), described previously (12, 15, 19), were used for tP_{CO_2} monitoring. One point tP_{CO_2} sensor calibration was performed *in vitro* according to the manufacturer's recommendations utilizing an 8% ± 0.05% CO_2 standard gas before placement. Calibration was repeated every 6 to 8 h, as indicated by the device. The V Sign sensor was attached to the base of the pig's right auricle utilizing a single use attachment ring. This area was chosen because the skin is not thick and because it is well perfused by a branch of external carotid artery. Before sensor placement, the attachment site was cleansed with isopropyl alcohol, and one drop of SenTec viscous contact gel was applied to the center of the sensor membrane. The V Sign sensor was heated to 43.5°C. Use of a heating element within the electrode elevates local skin temperature and causes hyperemia. Application of heat to the skin surface, promotes "liquefaction" or changes in the matrix of the dermal lipid component in the stratum corneum layer, which increases gas diffusion through the skin (20, 21). It has been reported previously (22) that such changes begin to occur at 41°C and reach optimal levels for maximal gas diffusion at 44°C. Therefore, local hyperemia improves correlation between transcutaneous and arterial CO_2 values. Previous publications (23, 24) indicated better $Paco_2$ correlation with increased electrode temperature; therefore, we used maximal temperature (43.5°C) allowed by the device. The SenTec monitor displays tP_{CO_2} values in mmHg as measured at 37°C without applying a temperature correction.

For Et_{CO_2} monitoring, a FilterLine H Set CO_2 sidestream sampling line and airway adapter were used, along with a Capnostream 20 system (Oridion Medical, Jerusalem, Israel). The FilterLine was changed daily or sooner if it became contaminated with secretions.

An i STAT blood gas analysis system (Abbot Point of Care, Princeton, NJ) and EG7+ cartridges were utilized for obtaining $Paco_2$ values. Paired measurements of Et_{CO_2} and $Paco_2$, and of tP_{CO_2} and $Paco_2$, were recorded every 6 h (as well as intermittently when clinically indicated) to assess the adequacy of ventilation. All measurements were done while animals were mechanically ventilated in the CMV mode.

Statistical analysis

SigmaPlot for Windows version 12.0 (Systat Software, San Jose, Calif) was used. Overlapping sets of data were analyzed based on (i) respiratory status (before vs. after the onset of ALI) and on (ii) hemodynamic status (stable vs. unstable). All results are expressed as mean ± SD. $P < 0.05$ was considered significant.

Linear regression was performed for pairs of $Paco_2$ and tP_{CO_2} as well as for pairs of $Paco_2$ and Et_{CO_2} data. Bias and 95% limits of agreement were calculated using Bland Altman analysis (25). Student *t* tests and analyses of variance with post hoc Holm Sidak multiple comparison tests were used.

RESULTS

A total of 454 h of animal intensive care unit care were provided during this study. We recorded 276 paired measurements of $Paco_2$ and Et_{CO_2}, and 250 paired measurements of $Paco_2$ and tP_{CO_2}, from eight animals. The average duration of monitoring was 56.8 ± 40.9 h. Et_{CO_2} and tP_{CO_2} measurements were made across a $Paco_2$ range of 25 to 85 mmHg. Animal data are presented in Table 1.

It is important to highlight that our injury model was fluid rather than static with rapidly declining respiratory status. The period between smoke/burn injury and onset of ALI was marked by pulmonary instability while animals progressed from healthy baseline conditions to ALI over 22.5 ± 10.6 h. The mean number of ventilator changes per hour was greater before onset of ALI (3.07 ± 1.53) than during ALI (1.84 ± 1.68, $P = 0.02$). Similarly, the average decrease in PFR in the first 24 h after injury was 199; in the second 24-h period, it was 100 (Fig. 1). There was a statistically significant decrease in PFR between baseline and 24 h, as well as between 12 and 24 h ($P < 0.05$), but not between 24 and 48 h ($P > 0.05$). During the study, two animals required norepinephrine infusion due to hypotension. During the study, we observed no thermal complications due to the placement of a heated tP_{CO_2} sensor on the auricle.

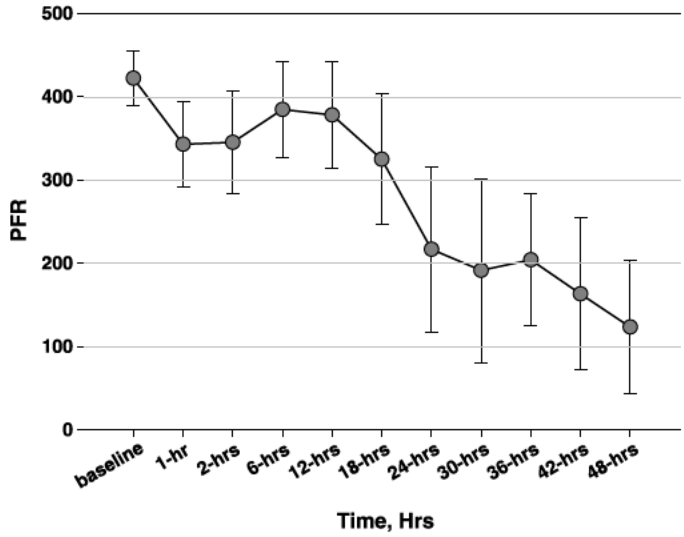

FIG. 1. **PFR during the first 48 h of study; at each time point, a single measurement was recorded from each animal (n = 8); error bars represent ± SD.**

Two partially overlapping sets of data were analyzed based on (i) pulmonary status (before vs. after the onset of ALI) and (ii) cardiovascular status (hemodynamically stable vs. unstable). The results of this analysis, describing the $Etco_2$-$Paco_2$ and $tPco_2$-$Paco_2$ relationships, are presented in Table 2 and are described in the following sections.

Before versus after the onset of ALI

Linear regression analysis of 105 $Etco_2$-$Paco_2$ pairs, recorded before the onset of ALI (Fig. 2A), demonstrated moderate correlation: $Paco_2 = 13.45 + 0.68 * Etco_2$ ($R^2 = 0.45$, $P < 0.0001$). There was systemic underreading by capnography ($P = 0.02$). Bland-Altman analysis revealed a mean bias of 0.91 ± 3.77 mmHg (Fig. 2B).

Analysis of 171 $Etco_2$-$Paco_2$ pairs, recorded after ALI (Fig. 3A), demonstrated low correlation: $Paco_2 = 41.51 + 0.34 * Etco_2$ ($R^2 = 0.12$, $P < 0.0001$). There was systemic underreading by capnography ($P < 0.001$). Mean bias increased to 14.84 ± 11.76 mmHg (Fig. 3B).

Analysis of 88 $tPco_2$-$Paco_2$ pairs, recorded before the onset of ALI (Fig. 2A), revealed moderate correlation: $Paco_2 = 17.01 + 0.56 * tPco_2$ ($R^2 = 0.51$, $P < 0.0001$). No systemic difference was observed ($P = 0.85$). Mean bias was 0.09 ± 4.56 mmHg (Fig. 2C).

Analysis of 140 $tPco_2$-$Paco_2$ pairs, recorded after the onset of ALI (Fig. 3A), revealed strong correlation: $Paco_2 = 7.74 + 0.83 * tPco_2$ ($R^2 = 0.78$, $P < 0.0001$). Slight systemic underreading was present ($P = 0.026$). Mean bias was 0.03 ± 5.44 mmHg (Fig. 3C).

Hemodynamically stable versus unstable

We repeated the analysis based on hemodynamic status. Linear regression of 233 $Etco_2$-$Paco_2$ pairs under hemodynamically stable conditions (Fig. 4A) demonstrated moderate correlation: $Paco_2 = 5.32 + 1.03 * Etco_2$ ($R^2 = 0.44$, $P < 0.0001$). There was systemic underreading by capnography. The mean bias was 6.74 ± 8.26 mmHg (Fig. 4B).

Analysis of 41 $Etco_2$-$Paco_2$ pairs under hemodynamically unstable conditions (Fig. 5A) did not demonstrate a linear relationship: $Paco_2 = 61.4 - 0.16 * Etco_2$ ($R^2 = 0.03$, $P = 0.29$). Systemic underreading was present ($P < 0.001$). Mean bias was 25.59 ± 15.30 mmHg (Fig. 5B).

Analysis of 212 $tPco_2$-$Paco_2$ pairs under hemodynamically stable conditions (Fig. 4A) demonstrated strong correlation: $Paco_2 = 7.86 + 0.82 * tPco_2$ ($R^2 = 0.80$, $P < 0.0001$). There was no systemic difference between the two techniques ($P = 0.29$). Mean bias was −0.35 ± 4.75 mmHg (Fig. 4C).

Finally, analysis of 38 $tPco_2$-$Paco_2$ pairs under hemodynamically unstable conditions (Fig. 5A) demonstrated poor correlation: $Paco_2 = 33.60 + 0.3 * tPco_2$ ($R^2 = 0.39$, $P < 0.0001$). There was systemic overreading ($P < 0.001$). Mean bias was −11.32 ± 14.87 mmHg (Fig. 5C).

DISCUSSION

In this study, we evaluated the utility of two commonly used noninvasive carbon dioxide monitoring technologies in a severely injured, mechanically ventilated porcine model of ALI due to smoke inhalation and burns. Our principal findings were (i) the period of time between smoke/burn injury and the onset of ALI was characterized by pulmonary instability, manifested by a steady decrease in the PFR and by frequent ventilator changes and other interventions; (ii) both $Etco_2$ and $tPco_2$ were moderately correlated with $Paco_2$ during this period; (iii) after

TABLE 2. **$Etco_2$-$Paco_2$ and $tPco_2$-$Paco_2$ relationships**

n (No. of pairs)	Variable compared with $Paco_2$	Condition	R^2	P	Bias, mean ± SD (95% limits of agreement), mmHg	Student t test, P
105	$Etco_2$	Pre-ALI	0.45	<0.0001	0.91 ± 3.77 (6.48 to 8.31)	0.02
171	$Etco_2$	ALI	0.12	<0.0001	14.84 ± 11.76 (8.21 to 37.89)	<0.001
88	$tPco_2$	Pre-ALI	0.51	<0.0001	0.09 ± 4.56 (8.85 to 9.03)	0.85
140	$tPco_2$	ALI	0.78	<0.0001	0.03 ± 5.44 (10.64 to 10.70)	0.026
233	$Etco_2$	HD stable	0.44	<0.0001	6.74 ± 8.26 (9.45 to 22.95)	<0.001
41	$Etco_2$	HD unstable	0.03	0.29	25.59 ± 15.30 (4.39 to 55.57)	<0.001
212	$tPco_2$	HD stable	0.80	<0.0001	0.35 ± 4.75 (9.67 to 8.97)	0.29
38	$tPco_2$	HD unstable	0.39	<0.0001	11.32 ± 14.87 (40.46 to 17.82)	<0.001

HD indicates hemodynamically.

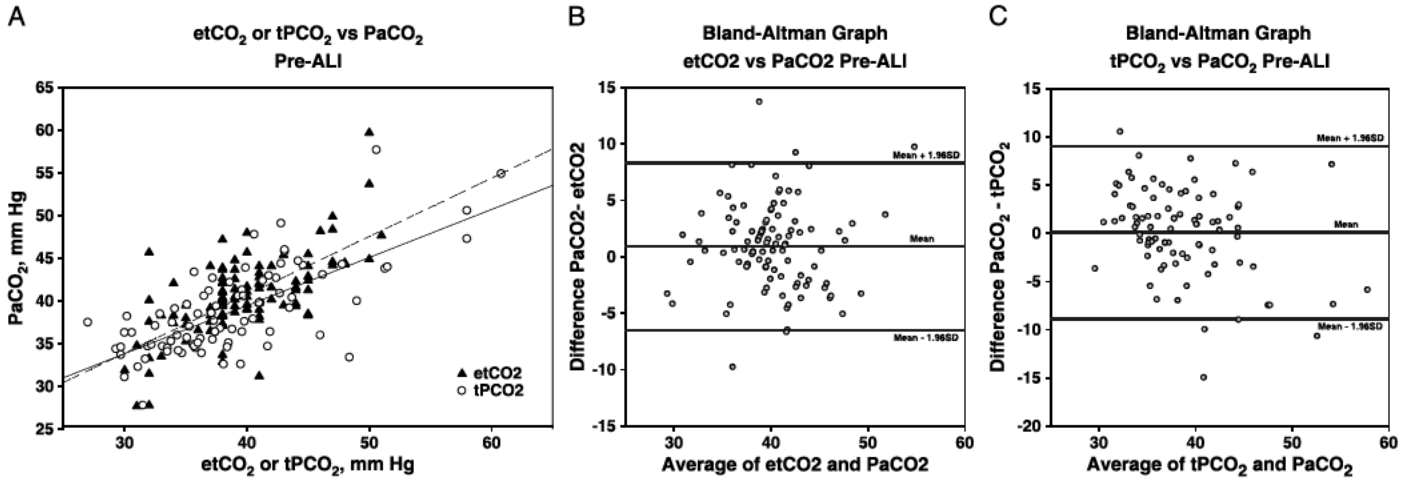

FIG. 2. **A, Scatter plot and linear regression analysis comparing $Etco_2$ and $Paco_2$ as well as $tPco_2$ and $Paco_2$ before the onset of ALI.** Solid line represents linear regression between $tPco_2$ and $Paco_2$. Dashed line represents linear regression between $Etco_2$ and $Paco_2$. B and C demonstrate Bland Altman analysis between $Etco_2$ $Paco_2$ and $tPco_2$ $Paco_2$ pairs; middle solid line indicates the mean difference (bias), and outer solid lines represent limits of agreement (mean ± 1.96 SD) between two methods.

the onset of ALI, $Etco_2$ became relatively inaccurate, whereas $tPco_2$ did not; (iv) hemodynamic instability caused $Etco_2$ values to lose their linear relationship with $Paco_2$. Based on these observations, we conclude that both methods can be useful in the monitoring of patients with developing severe lung injury, but that caution should be used in the interpretation of results when patients are changing rapidly.

Good correlation between $Etco_2$ and $Paco_2$ across all ranges of dead space was reported by McSwain et al. (7). Our previous study (26) demonstrated close correlation between $Etco_2$ and $Paco_2$ in a porcine model of severe chest injury during periods of hemodynamic stability and during settings of hypoventilation and hyperventilation induced by varying tidal volumes and different respiratory rates in healthy swine. At the same time, results were not as promising when accuracy of capnography was evaluated in trauma patients (6). In addition, several studies compared accuracy of end-tidal and $tPco_2$ monitoring in human patients (13, 27, 28), favoring $tPco_2$. In our study, $Etco_2$ systemically underestimated $Paco_2$. Presence of systemic bias was confirmed by paired Student *t* test results (Table 2). This is to be expected, particularly in patients with developing ALI, in whom dead space progressively increases, thereby leading to an increase in $Paco_2$-$Etco_2$ gradient.

There was moderate correlation between $tPco_2$ and $Paco_2$ ($R^2 = 0.51$) before ALI. This correlation became more linear ($R^2 = 0.78$) after onset of ALI. We expected better correlation during pre-ALI stage, and such findings were surprising. We speculate that lower $tPco_2$-$Paco_2$ correlation before onset of ALI was possibly due to more frequent ventilator changes: approximately 3.07 ± 1.53 changes per hour in the initial phase of the experiment, compared with 1.84 ± 1.68 changes per hour after the onset of ALI. Also, more frequent suctioning was required in the first 24 h after injury due to copious secretions. Because it can cause alveolar collapse and loss of recruitment, repeated suctioning may have had a destabilizing effect on $Paco_2$ correlation. In addition, the $tPco_2$ sensor was more frequently disconnected and removed from the animals during the first 24 h of the experiment to accommodate bronchoscopies.

When the $tPco_2$-$Paco_2$ relationship was examined based on hemodynamic status, it was strongly linear ($R^2 = 0.80$) with

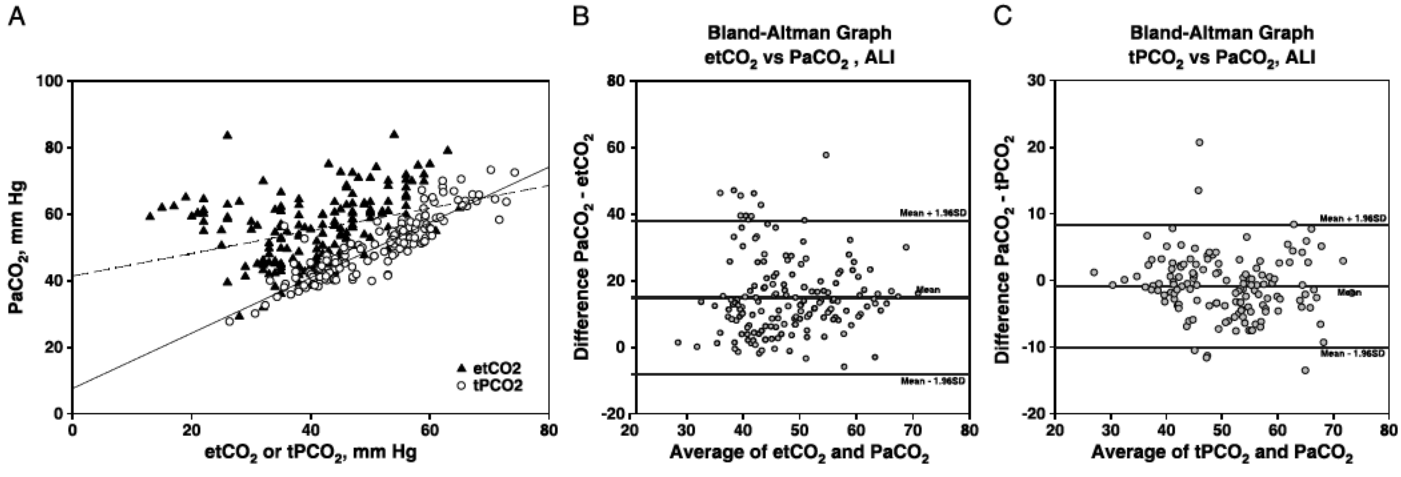

FIG. 3. **A, Scatter plot and linear regression analysis between $Etco_2$ and $Paco_2$ as well as $tPco_2$ and $Paco_2$ after the onset of ALI.** Solid line represents linear regression between $tPco_2$ and $Paco_2$. Dashed line represents linear regression between $Etco_2$ and $Paco_2$. B and C demonstrate Bland Altman analysis between $Etco_2$ $Paco_2$ and $tPco_2$ $Paco_2$ pairs; middle solid line indicates the mean difference (bias), and outer solid lines represent limits of agreement (mean ± 1.96 SD) between two methods.

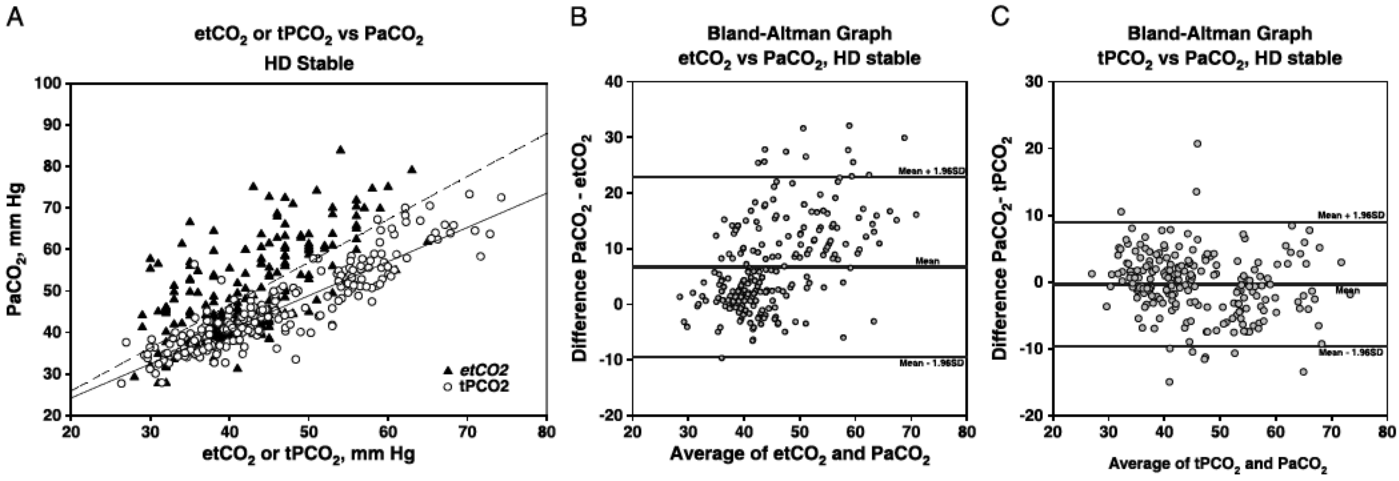

FIG. 4. **A, Scatter plot and linear regression analysis between $Etco_2$ and $Paco_2$ as well as $tPco_2$ and $Paco_2$ during hemodynamic stability (HD stable).** Solid line represents linear regression between $tPco_2$ and $Paco_2$. Dashed line represents linear regression between $Etco_2$ and $Paco_2$. B and C demonstrate Bland Altman analysis between $Etco_2$ $Paco_2$ and $tPco_2$ $Paco_2$ pairs; middle solid line indicates the mean difference (bias), and outer solid lines represent limits of agreement (mean ± 1.96 SD) between two methods.

minimal bias (−0.35 ± 4.75 mmHg) as long as MAP remained greater than 60 mmHg. Our results confirm those reported previously in human studies (11, 13, 20, 27, 28) that demonstrated similar correlation. $tPco_2$ had a less linear correlation to $Paco_2$ during hemodynamic instability ($R^2 = 0.39$). In addition, transcutaneous monitoring tended to overestimate $Paco_2$ under these conditions. Previous reporting (29, 30) indicated that vasoactive medications did not have a significant effect on $tPco_2$ monitoring accuracy. However, our results were different, possibly because of the sensor location on the right auricle. Although the animals were hypotensive, their ears were cold to touch, and there was a visible area of vascular congestion. Preferred locations for $tPco_2$ monitoring have been reported in humans (9, 10), but no such location has been defined in pigs.

Because we used a subset of animals for this work from a larger study, which pursued treatment of ARDS due to smoke inhalation and burns, the samples we obtained were convenience samples. This limited our ability to further investigate effects of suctioning, ventilator changes, and sensor disconnections on stabilizations/steady state times of the measured variables. Future studies designed specifically to address these limitations may be warranted.

Based on our data, transcutaneous capnometry is an acceptable trend-monitoring the tool in settings of lung injury in hemodynamically stable patients and may be useful in a prehospital environment. However, the current generation of $tPco_2$ sensors has some limitations. First, the $tPco_2$ sensor requires stabilization time after placement. Several articles (31, 32) recommended a 20-min stabilization time while using the SenTec Monitor. Second, to maintain accuracy, the sensor has to be regularly recalibrated *in vitro*. Recalibration frequency appears to depend on sensor temperature. At 43.5°C, recalibrations were required every 6 to 8 h. On average, recalibration can be completed in approximately 3 min. Afterward, the sensor is repositioned on a patient and again requires stabilization time. In our experience, about 25 to 30 min was spent on moving, cleaning, recalibrating, replacing, and waiting for the sensor to stabilize. In this study, because of previously described limitations, we could not establish the precise stabilization timing necessary for improved accuracy; further study should be considered to

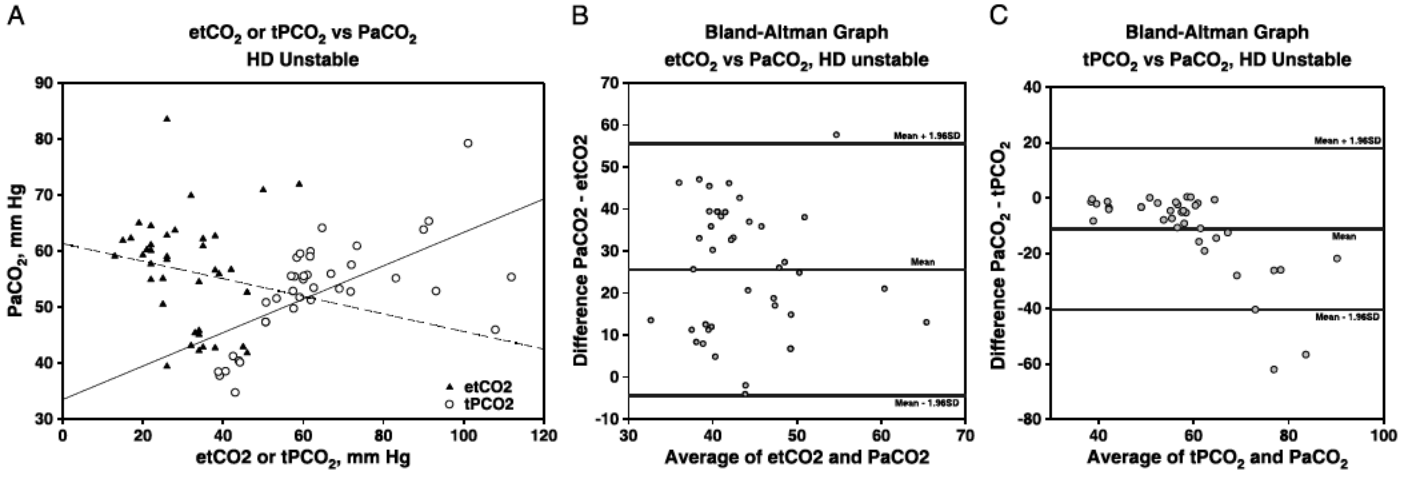

FIG. 5. **A, Scatter plot and linear regression analysis between $Etco_2$ and $Paco_2$ as well as $tPco_2$ and $Paco_2$ during hemodynamic instability (HD unstable).** Solid line represents linear regression between $tPco_2$ and $Paco_2$. Dashed line represents linear regression between $Etco_2$ and $Paco_2$. B and C demonstrate Bland Altman analysis between $Etco_2$ $Paco_2$ and $tPco_2$ $Paco_2$ pairs; middle solid line indicates the mean difference (bias), and outer solid lines represent limits of agreement (mean ± 1.96 SD) between two methods.

address this issue. Also, we should point out that a prolonged stabilization time may limit utilization of $tPCO_2$ monitors in prehospital environments. Finally, the sensor membrane requires replacement every 42 days and between patients. Currently, several companies are developing next-generation solid-state $tPCO_2$ sensors that may overcome these shortcomings. Given promising results obtained from the use of a transcutaneous CO_2 sensor, these new developments will be a welcomed addition to critical care monitoring armamentarium as well as potentially opening new possibilities for servo controlling mechanical ventilators and extracorporeal life support devices.

CONCLUSIONS

In a porcine model of ALI due to smoke inhalation and burns, transcutaneous CO_2 monitoring is an acceptable noninvasive surrogate for $PaCO_2$ under hemodynamically stable conditions and can be useful as a trend monitoring tool. However, $tPCO_2$ readings should be correlated with $PaCO_2$ with increased frequency when a patient's condition is dynamically changing, for example, during periods of hemodynamic instability. End-tidal CO_2 monitoring offers an ease-of-use advantage over the current generation of transcutaneous CO_2 monitors. However, $EtCO_2$ readings should be correlated with $PaCO_2$ with increased frequency during evolution of lung injury (changes in dead space).

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